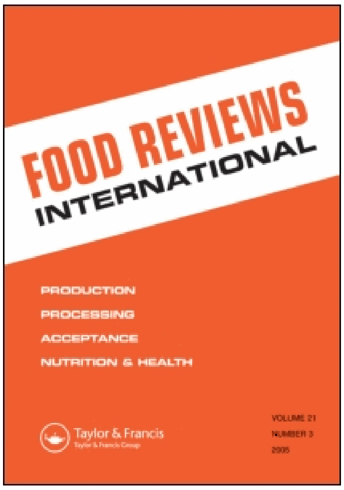

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COVER CROPS IN SUSTAINABLE FOOD PRODUCTION

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ABSTRACT

Cover crops are important components of sustainable agricultural systems. They increase surface residue and aid in the reduction of soil erosion. They improve the structure and water-holding capacity of the soil and thus increase the effectiveness of applied N fertilizer. Legume cover crops such as hairy vetch and crimson clover fix nitrogen and contribute to the nitrogen requirements of subsequent crops. Cover crops can also suppress weeds, provide suitable habitat for beneficial predator insects, and act as non-host crops for nematodes and other pests in crop rotations. This paper reviews the agronomic and economic literature on using cover crops in sustainable food production and reports on past and present research on cover crops and sustainable agriculture at the Beltsville Agricultural Research Center, Maryland. Previous studies suggested that the profitability of cover crops is primarily the result of enhanced crop yields rather than reduced input costs. The experiments at the Beltsville Agricultural Research Center on fresh-market tomato production showed that tomatoes grown with hairy vetch mulch were higher yielding and more profitable than those grown with black polyethylene and no mulch system. Previous studies of cover crops in grain production indicated that legume cover crops such as hairy vetch and crimson clover are more profitable than grass cover crops such as rye or wheat because of the ability of legumes to contribute N to the following crop. A comparative analysis of four reduced-tillage corn based cropping systems at the Sustainable Agricultural Demonstration site showed that the cover crop system with corn following hairy vetch produced the largest average gross margin, followed by the conventional no-tillage system, a manure-based system, and a crown vetch living mulch system. The EPIC model to simulate the long-term economic and environmental impacts of incorporating cover crops into grain production systems in mid-Atlantic states was used. Results based on 60 simulation years indicated that there are tradeoffs between the competing objectives of increased profitability, lower soil erosion, and reduced nutrient and pesticide hazards to surface and groundwater supplies. A corn/soybean two-year rotation was found to be the most profitable, while the cover crop system and the manure system were found to be the most environmentally sound.

INTRODUCTION

Public concern about contamination of the environment by agricultural chemicals, soil erosion, depletion of natural resources, and pesticide residues in foods have prompted shifts to sustainable production systems. Major practices used in sustainable agriculture production include crop rotations, reduced tillage, use of animal manures, and cover crops. Cover crops are an important component of sustainable crop rotations.

While the practice of growing cover crops is old, the role of cover crops in agriculture has changed over time. Earlier cover crops were plowed under as green manures or used as animal feed in drought seasons. Recently, new roles and better use of cover crops were developed. The newest, most conspicuous management practice for using cover crops is in no-tillage or reduced tillage farming systems. This practice extended the usefulness of the residues (slower breakdown), and utilized them as mulches to replace plastic mulches (in vegetable production), suppress weeds, reduce soil erosion, maintain better soil moisture, and make better use of their nutritional content. The roles of cover crops in fixing nitrogen, recycling nutrients, and reducing soil compaction by their roots have been documented. However, economic studies to evaluate the benefits against production costs of cover crops have been lacking.

The objectives of this article are to 1) review current knowledge of using cover crops to improve sustainability of horticultural and grain production; 2) evaluate profitability and economic risk of sustainable vegetable and grain production using cover crops with emphasis on research at the Beltsville Agriculture Research Center in Maryland; and 3) evaluate the long-term effects of cover crops in crop rotations at the Sustainable Agricultural Demonstration site in Beltsville, Maryland.

REVIEW OF LITERATURE

Cover crops can occupy many niches in crop rotations worldwide. In northern temperate areas, the most common types of cover crops are winter annuals that are grown during the off-season winter months and summer annuals or perennials that are grown during part or all of the cropping season (e.g., grass strips between rows of orchard trees). The use of winter annual cover crops grown between crop harvest in the fall and crop planting the following spring will be emphasized. Winter annual cover crops can be planted after crop harvest or overseeded into a standing crop before harvest with the intent of establishment before winter. Cover crops must produce sufficient biomass in fall and/or spring to provide the desired ecological benefits.

Cover Crop Species

There are numerous winter annual species that can be used for cover crops, particularly in coastal and southern areas with mild winters (1,2). A selection of cover crops commonly used in the United States is listed in Table 1. Rye is among the most reliable cover crops because of its winter hardiness. It produces rapid growth during cool fall weather resulting in superior erosion protection and N recovery. Barley and annual ryegrass can provide services similar to those provided by rye. Oats also grow rapidly in cool fall weather but winterkill. This eliminates the need for killing the cover crop in spring but results in less biomass production for oats than for either rye or barley.

Hairy vetch is the most widely used winter annual legume because of its winter hardiness, its high productivity, and its high N content. Woollypod vetch, Austrian winter pea, and crimson clover are also efficient N producers but have fewer degrees of winter hardiness and adaptability than hairy vetch. Subterranean clover has good potential for suppressing weeds because of its low, dense growth habit but has poor winter hardiness. Brassica species have potential for use as a soil fumigant because the high glucosinolate content of their foliage can decompose to toxic isothiocyanates. Buckwheat can provide rapid ground cover during short intervals between crops but neither tolerates frost nor produces much biomass (2).

Cover crops exhibit wide variation in the quantity and quality of biomass yield. Biomass yield varies among and within species depending on soil, moisture, temperature, and the length of the growing season. Biomass yields of hairy vetch, crimson clover, cowpeas (*Vigna unguiculata*), and Australian winter peas range from 3 to 5 t ha^{-1}. Among the highest biomass yielders are annual ryegrass, rye, berseem clover (*Trifolium alexandriuum*), sorghum–sudangrass, and woollypod vetch (*Vicia villosa* spp. *dasycarpa*) which may reach up to 10 t ha^{-1} of biomass with 2 to 3 cuttings per growing season (2).

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Table 1. Cover Crops Commonly Used in the United States

Common name	Scientific name	Primary benefits
Grasses:		
Rye	*Secale cereale* L.	Erosion control and N recovery most winterhardy cover crop
Barley	*Hordeum vulgare* L.	Erosion control and N recovery
Oat	*Avena sativa* L.	Fall cover that winterkills
Annual ryegrass	*Lolium multiflorum* Lam.	Erosion control and N recovery
Sorghum–Sudangrass	*Sorghum bicolor* (L.) Moench × *S. sudanense* (Piper) Stapf	Summer biomass production
Legumes:		
Hairy vetch	*Vicia villosa* Roth	N production, most winter-hardy legume
Woollypod vetch	*Vicia dasycarpa* L.	N production
Austrian winter pea	*Pisum sativum* ssp. *sativum* var. *arvense* (L.) Poir.	N production
Crimson clover	*Trifolium incarnatum* L.	N production, early maturity
Subterranean clover	*Trifolium subterraneum* L.	Effective weed suppression
Berseem clover	*Trifolium alexandrinum* L.	Summer biomass production
Cowpea	*Vigna unguiculata* (L.) Walp	Heat tolerance
Other:		
Mustard species	*Brassica* spp.	Potential fumigation effects
Buckwheat	*Fagopyrum esculentum* Moench	Short season ground cover

The quality of biomass also varies from species to species. When seeds are inoculated at planting time, legumes generally fix and accumulate substantial amounts of N. Legume cover crops can contribute substantially to the N requirement of crops because of their high biomass and N content which ranges from 2.5 to 4 percent. Because of the low C/N ratio, which can be as low as 10, legume biomass serves as a rapidly decomposable material and provides ample nutrients to the subsequent crop (3,4). In contrast, grass species have a high C/N ratio that can reach up to over 50 at maturity. Their residues decompose more slowly than legumes.

Benefits of Cover Crops

Erosion Control

Soil erosion presents a serious threat to the long-term productivity of agricultural lands (5). Research demonstrates that corn yields are decreased by an average of 10% on severely eroded soils in the north central region (6). Elimination of tillage alone has helped control erosion as well as improve soil quality. Mahboubi et al.

(7) showed that organic carbon, cation exchange capacity, and a number of physical properties were improved after 28 years of no tillage compared to moldboard or chisel plowing. Karlen et al. (8) found that surface residue can play a significant role in improving soil physical, chemical, and biological properties in no-tillage systems. Cover crops can provide large quantities of surface residue as well as a soil-stabilizing root system, particularly when grass species such as rye are used. As a result, cover crops have long been considered a primary tool for reducing erosion and improving soil quality (9). Perennial cover crops are particularly effective at preventing erosion in perennial cropping systems such as orchards where they require little management and do not require annual reseeding.

N Fixation and Nutrient Recycling

Legume cover crops fix N and may contribute most of the N requirement of crops such as corn (10) or tomato (11). Total N content of medics and crimson clover biomass reaches 50 to 150 kg ha^{-1}, whereas, total N content for berseem, hairy vetch, woollypod vetch, and subterranean clover biomass may reach or exceed 200 kg ha^{-1}.

Cover crops can also play an important role in recycling N and other nutrients. Conservation of nutrients by recycling is of special importance in sandy soils with low capacity to hold nutrients and water. Table 2 shows macro- and micronutrients recycled by ‘Iron Clay’ cowpeas, ‘Lana’ woollypod vetch, and ‘Seco’ barley grown as cover crops in a date orchard under basing irrigation in southeast California (11). In addition, significant amounts of nutrients can be sequestered and recycled by cover crops during the reclamation process of soils with high salinity. Depending on the level of salinity in the soil, reclamation requires several seasons during which the field is flooded with water to wash down the salt. Planting salt tolerant cover crops such as Seco barley and sorghum–sudangrass during the reclamation process will promote recycling appreciable amounts of nutrients that would have been washed into the deeper zones of the soil profile.

Table 2. Nutrients Recycled by Cover Crops Grown in a Date Orchard in Coachella Valley, California

Cover crop	th^{-1} Biomass	N	P	K	Ca	Mg	Mn	Fe	Cu	B	Al	Zn
		Kg ha^{-1}										
‘Iron Clay’ cowpea	5.0	123*	17	177	0.10	0.02	0.17	10.8	0.05	2.3	7.5	0.2
‘Lana’ vetch	4.7	160*	13	171	0.06	0.02	0.15	8.9	0.06	0.2	9.2	0.1
‘Seco’ barley	4.1	73	8	99	0.01	0.01	0.06	4.6	0.05	0.1	—	0.1

Source: Abdul-Baki et al., 1998 (13).
* N in legume tissue derived from both N fixation and recycling soil N.

Weed Control

Cover crops suppress weeds either by smothering growth of established weeds or creating an environment that interferes with weed emergence and establishment (12). Cover crop species that emerge and grow rapidly are most effective in smothering weeds. Vigorous species that produce high biomass yields are often the most effective competitors that deprive weeds of light, water, and nutrients. Winter annual cover crops are particularly adapted to developing a dense canopy in early spring that prevents establishment and growth of annual weeds later in season.

After a cover crop is killed, residue can inhibit the establishment of weeds through a number of mechanisms (12). If the residue remains on the soil surface, it can eliminate environmental cues required for weed seed germination such as light or alternating temperature. Residue can also act as a physical barrier that impedes the emergence of weed seedlings after germination. Phytotoxic (allelopathic) compounds released by residue can inhibit germination and growth of weeds. In contrast, cover crop residue may encourage weed emergence in selected circumstances, either when residue maintains soil moisture at a level suitable for germination during droughty periods or when germination-stimulating compounds such as nitrates are released. Weed suppression by cover crop residue is generally observed early but not for the duration of the growing season. Cover crops need to be integrated with other techniques to obtain optimum weed control.

Soil Moisture

Cover crops affect soil moisture in many ways. Long-term cover crop use builds soil organic matter and increases its water holding capacity. In the short term, cover crop residue protects the soil from the impact of raindrops and improves infiltration of rainfall moisture into soils (14). Cover crop residue also can intercept radiation thereby cooling soils and slowing evaporation (15). Soils covered with cover crop residues can be more manageable than bare cultivated soils and may permit farm workers and machinery to operate shortly after rain.

Pest Control

Cover crops have been shown to affect insect, pathogen, and nematode pests (16). Bugg and Wilson (17) found that generalist predators may be important in the biological control of insects that attack warm-season vegetable crops. They observed that during periods when pests are scarce or absent, several important predators subsisted on nectar, pollen, and alternative prey offered by cover crops. Bugg et al. (18) have shown that the flower bug [*Orius incidiosus* (Say)], big-eyed bugs (*Geocoris* spp.), and various lady beetles (Coleoptera coccinellidae) attained high densities in various vetches, clovers, and certain *Cruciferae*. These predators subsisted and reproduced on nectar, pollen, thrips, and aphids and were established before the arrival of key pests (19–23). In these studies, narrow strips of hairy vetch and crimson clover were maintained along the borders of tomato fields. Insect predators used the cover crops as host plants and then moved into the tomato crop. Stark (24) reported that when sweet corn was incorporated into a potato rotation in Idaho, and the residues were turned under, Virticillium wilt (*Virticillium dahliae*) population in the soil declined.

Recently, priority has been given to developing biological approaches to control phytopathogenic nematodes in vegetable and strawberry systems as alternatives to methyl bromide. Several field and cover crops (cereals and legumes) have been identified as non-hosts to nematodes. Rapeseed and sudangrass green manures grown prior to potatoes at Prosser, Washington State, provided 72 and 86 percent control of the root-knot nematodes on potatoes, respectively (24). Cereals, such as rye, bahiagrass, and barley, are non-hosts to root-knot nematodes (25). Other non-host cover crops include several lines of cowpeas (26), marigold (*Tagetes patula*), hairy indigo (*Indigofera hirsuta*), sunn hemp (*Crotalaria junda*), velvetbean (*Mucuna deeringiana*), and castorbean (27). It is likely those crop rotations that utilize non-host cover crops and nematode-resistant horticultural and field crops in well-planned production rotations will reduce the need for chemical nematicides (28).

Limitations of Cover Crops

Land Lease and Small Parcels

A significant portion of agricultural farm land is leased, usually on a five-year term. Leasing is popular among farmers or corporations who do not wish to invest the money in acquiring land but would rather use the available capital to lease land and expand their operations when the market is favorable for more production. Growers who lease such land try to get the most out of the field or vegetable crops they grow with the least investment. Fertility of such land declines with time due to absence of a long-term commitment to land stewardship. An almost identical situation exists in many countries of the world where land parcels are barely adequate to produce food for the family and the land is kept under intensive food production all year round. In both scenarios, long-term improvements in soil tilth and fertility are unlikely to occur because cover crops are not used.

Water Limitations

In areas where rainfall is seasonal or limiting, cover crops may consume water that is needed by the cash crops. Even in humid areas such as the eastern United States, crop moisture demands may not be met in droughty summers if cover crops remove soil moisture in spring. In addition, competition for moisture and nutrients between cover crops used as living mulches and the cash crop can limit the usefulness of this approach unless the living mulch is suppressed by herbicides or other management approaches that limit this competition (12).

Financial Limitations

To get the most benefits out of cover crops, they should be terminated leaving the residues on the surface of the ground to serve as mulches and to provide a longer lasting effect in suppressing weeds. This situation can be best achieved if the cover crops are part of a no-tillage (or reduced tillage) farming system. Transfer from conventional to alternative no-tillage systems requires new farming equipment including no-tillage seeders, transplanters, and mowers. Many farmers cannot afford this investment and some have reservations about whether the alternative system offers sufficient advantages to justify the investment.

Length of the Growing Season

Cover crops are best adapted to areas where the growing season is long enough to support one main crop and establishment of a cover crop during the remainder of the year. Such a system will protect the soil from erosion and improve fertility. However, cover crops reduce soil temperature by several degrees compared to bare soil or soil covered with polyethylene mulch and, consequently, delay the maturity of the main crop by several days or even longer (29,30). This phenomenon could cause a problem in cooler, northern climates where the growing season is barely long enough to allow the maturity of the cash crop.

Hosts to Pests

Cover crops species must be carefully selected taking into account the common pests that affect both the main crop and the field or horticultural crop. Insect and pathogens could use the cover crop as a host during the off season, multiply, and spread to the main crop in the following season. Phytopathogenic nematodes and many insect species have a large number of hosts. During the off season, they may survive on cover crops that serve as favorable hosts. Tropical and subtropical conditions with high temperature and moisture are conducive to their growth. Their populations continue to grow and, by the time the main crop is planted, they can inflict severe economic losses. Use of non-host cover crops in a production rotation is a safe practice especially when coupled with appropriate crop rotations.

Cover Crop Management

The management of cover crops often requires tradeoffs in an attempt to optimize their benefits and minimize their detrimental effects. Important management choices include cover crop species, timing of cover crop planting and kill, method of kill, and degree of tillage. Many of the tradeoffs involved in cover crop management will be highlighted in discussions of vegetable and grain production in subsequent sections.

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Effectiveness of cover crops in controlling weeds also depends on the way the cover crop is terminated. The oldest method of termination is plowing under. This method disturbs the soil and mixes the residues with it thus putting the residues in close contact with soil microorganisms. The process speeds up decomposition, mineralization of organic matter, and the release of nutrients to the following crop. In addition, when cover crops are plowed under, they can no longer be used as mulches to suppress weed growth and can often stimulate the germination and growth of new weed seeds.

The most effective way of using cover crops for weed control is to kill them chemically, mechanically or both, and keep the residues on the surface of the soil. Chemical killing by herbicides is the conventional approach in no-tillage crop production (31). Organic farmers and home gardeners, on the other hand, prefer mechanical killing usually with a flail mower to chop the cover crops into small pieces and scatter the residue to form a mulch layer. If packed well, it suppresses weeds for several weeks depending on the mass and decomposition rate of the mulch (32).

Rolling the cover crop is the most recent development in cover crop management that has not been utilized fully. The roller damages the plants by lodging them severely and by successive crimping of cover crop stems, keeping the above ground part of the plant attached to the root system. Rolled plants decompose more slowly than those killed by mowing and, consequently, control weeds for a longer period of time.

In orchards, cover crops may not require termination. They may be left until they form seeds and die. Unless they interfere with orchard management operations, this practice would results in the highest biomass production, the most effective weed control, and economic savings on reseeding.

The Economics of Cover Crops in Horticultural Crop Production

Several studies have investigated the economic feasibility of incorporating cover crops into horticultural production. Most of these studies are relatively recent and use one to three years of experimental data. Therefore, these studies may be interpreted as short-term budgetary studies reporting preliminary findings. The main economic focus of these studies is savings in input costs from reduced pesticide and fertilizer applications and use of plastics.

Creamer et al. (33) used a budgetary analysis to determine if using cover crops to reduce chemical inputs increases the profitability of processing tomato production systems. The authors used data from experiments conducted during 1992 through 1993 at two locations in Ohio (Columbus and Fremont) to calculate economic returns above variable costs. Four processing tomato production systems were evaluated in the study: 1) conventional with no cover crops; 2) integrated production with cover crops and fewer pesticides applied; 3) organic production with cover crops and mechanical weed control; and 4) cover crops with no additional inputs. The cover crop systems used a mixture of hairy vetch, rye, crimson clover, and barley. At the Columbus location, the authors found no significant difference in economic returns between the four production systems. At the Fremont location, the conventional system produced the largest economic returns. The cover crop treatments at this location produced lower red fruit yields than the conventional treatment.

Wyland et al. (34) examined impacts of using cover crops in broccoli production on soil N dynamics, insect populations, incidence of plant diseases, input scheduling, tillage, and economic costs. The winter cover crops evaluated were phacelia, Merced rye, and fallow. The authors used one year of cover crop field trial data (1992–1993) from a site located in the Salinas Valley of California. The authors found the costs of cover crops to be minor relative to the costs of conventional winter management of fallowed fields and the costs of broccoli production.

Brunson et al. (35) evaluated the economic feasibility of using alternative eggplant production systems in southern Georgia. The authors compared the traditional rye cover crop system with chemical pest control to clover cover crop systems (crimson clover and subterranean clover) in which beneficial predator insects are used to reduce chemical applications during the production season. They used multi-year data from field trials conducted on four research farms of the Coastal Plain Experiment Station at Tifton, Georgia, to calculate net return distributions for each eggplant production system. They used stochastic dominance and expected value (EV) criteria to rank the systems according to risk efficiency. The conventional rye system dominated the clover systems under both EV and first degree stochastic dominance criteria at all four locations. These results occurred despite smaller input costs for the clover systems when compared to the conventional system. They concluded that alternative eggplant systems utilizing clovers are not economically comparable with the conventional rye system under their experimental setting due to large yield differentials between the conventional system and the cover crop systems.

Klonsky and Livingston (36) evaluated the profitability of low-input and organic farming systems for crop and vegetable production in the Sacramento Valley of California. A representative four-year rotation of processing tomatoes, safflower, corn, and a double crop of either winter legume or grain with dry beans was compared to a conventional two-year rotation (tomatoes and wheat), a low-input system, and an organic system using four years of experimental data from the Sustainable Agriculture Farming Systems (SAFS) project at the University of California, Davis. Lana woollypod vetch was used as a cover crop before tomato, safflower, and corn in the alternative systems (low-input and organic systems) and was used primarily for fertility management. The authors found fuel and labor costs to be greater for cover crop management than for application of synthetic fertilizer. Fertility management with cover crops preceding tomatoes and corn exhibited great variation from year to year and proved to be the most challenging component for the alternative farming systems.

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Thus, they concluded more research needs to be done to improve fertility management with cover crops.

Nwonwu and Obiaga (37) investigated the costs and benefits of using leguminous cover crops in place of hand weeding to control weeds in young pine plantations in the Rain Forest Zone of Nigeria. The authors used present value of costs and net present value analysis. The cover crops evaluated were *Calapogonium mucunoides* Desv., *Centrosema pubescens* Benth., and *Pueraria phaseoloides* (Rexb.) Benth. Hand weeding was the most labor intensive and costly of the four weed control methods evaluated. The hand-weeding method also had a negative net present value, while the three leguminous cover crop methods had positive net present values. The *C. mucunoides* method had the largest net present value, the largest tree survival percentage, and the highest average tree heights of the four methods evaluated. The authors concluded that using cover crops to control weeds in young pine plantations is more economical than hand weeding.

Kelly et al. (38) compared the profitability of fresh-market tomato production using a hairy vetch cover crop to using the traditional polyethylene mulch system and a no-mulch (bare soil) system. The results indicated that the hairy vetch system was the most profitable system and least risky among the three systems in all years and under all weather conditions. A detailed description of this study will be presented later in this paper.

It appears from the studies cited above that research investigating the profitability of cover crops in horticultural systems is still in the beginning stages. Two studies (33,34) use only one year of data. Clearly, more years of data are needed to evaluate the long-term profitability of cover crops in horticultural systems. Nevertheless, one can speculate from the review of the work completed thus far that reducing input costs with cover crops may not be enough to increase profitability. It appears that crop yields must also be enhanced. In the studies where cover crops were found to be unprofitable (33,35), crop yields for the cover crop systems were lower than those for the conventional systems. In the two studies where cover crops were found to be more profitable than conventional systems (37,38), reduced input costs were accompanied by enhanced yields.

The Economics of Cover Crops in Grain Production

More studies have evaluated the profitability of cover crops in grain production than in horticultural production. The majority of grain production studies have focused on incorporating cover crops into no-tillage corn production systems. The most common cover crops evaluated were hairy vetch, crimson clover, winter wheat, and rye. Many studies evaluated only the average profitability of cover crop systems. Some evaluated both the average profitability and the variability of economic returns. Two studies used production functions to estimate profit-maximizing levels of N fertilizer for various cover crop systems, while two studies evaluated gains in energy efficiency from using legume cover crops in place of commercial N fertilizer.

Average Profitability

Frye et al. (39) evaluated the economic and agronomic effects of winter cover crops combined with no-tillage on corn production in Kentucky. Cover crops included corn residue, rye, crimson clover, big flower vetch, and hairy vetch. Corn yields were greatest with a hairy vetch cover crop and 100 kg ha^{-1} applied N. However, legume cover crops alone did not provide enough N to produce as much corn as was obtained from legume cover crops combined with fertilizer N. Net returns above direct expenses were highest each year for the hairy vetch treatment with 100 kg ha^{-1} applied N. Net returns varied more from year to year with cover crops and no fertilizer N applied than with combinations of cover crops and applied fertilizer N. They concluded that no legume by itself provided adequate N for corn production.

Shurley (40) evaluated corn yields and net returns for different cover crop treatments in no-tillage corn production in Kentucky. Cover crops included corn residue, rye, bigflower vetch, and hairy vetch. Average corn yields were highest on the bigflower vetch and hairy vetch plots with added N. Both bigflower vetch and hairy vetch produced average net returns that were nearly equivalent to those of the corn residue (conventional) treatment.

Allison and Ott (41) reviewed studies investigating the economics of using legume cover crops in conservation tillage systems. The authors concluded that legume cover crops are profitable if they enhance the yield of the succeeding crop but are unprofitable if used as the sole source of N in the cropping system. They further concluded that N prices would have to increase considerably for legume cover crops to become cost-effective N sources.

Bollero and Bullock (42) investigated the feasibility of using cover crops in both corn and grain sorghum production in the central Corn Belt. Cover crops were hairy vetch, rye, and fallow. Hairy vetch produced greater grain sorghum yields than the two other cover crops. Grain sorghum following hairy vetch required less optimal N than corn following hairy vetch, but the corn system was still more profitable. In addition, the cost of hairy vetch establishment in the grain sorghum system exceeded the rotational benefits (the value of hairy vetch N contribution plus the value of additional grain yield). Thus, they concluded that grain sorghum cover crop systems were not attractive alternatives to corn systems in the central Corn Belt.

Stute and Posner (43) investigated the profitability of using crimson clover and hairy vetch in oat/corn two-year rotations in the upper Midwest. The authors used data from a field study conducted from 1989 to 1993 near Arlington, Wisconsin. They found that an oat/crimson clover–corn rotation produced nearly the same average gross margin as either continuous corn or a two-year oat/corn rotation. The crimson clover system was more profitable than the hairy vetch system because of lower seeding costs for crimson clover when compared with hairy vetch. They concluded that legume cover crops have great potential for reducing N fertilizer application in Midwest corn production without economic penalty to producers.

Energy Savings

Ott (44) investigated both the profitability and the energy efficiency of using crimson clover in grain sorghum production in northern and southern Georgia. The author compared the economic returns and energy savings of using crimson clover to those of using either stubble or a grass (rye or wheat) cover. Energy efficiency was evaluated by comparing the direct energy used in sorghum production for each cover crop system. Direct energy was defined as the amount of energy invested in variable inputs. Crimson clover was more energy efficient than either grass or stubble cover. However, crimson clover produced the smallest average returns. The author concluded that using crimson clover as a cover crop in Georgia grain sorghum systems does not pay.

Ess et al. (45) evaluated the energy requirements and the economic returns associated with using legume cover crops in corn production. The objective of the study was to determine if using legume cover crops as substitutes for N fertilizer would significantly reduce the energy required for corn production. The authors evaluated two tillage treatments (no-tillage, where the cover crop was killed by herbicides, and disking, where the cover crop was killed by spring disking) and five cover crops (rye, hairy vetch, bigflower vetch, a combination of hairy vetch and bigflower vetch, and a combination of rye, hairy vetch, and bigflower vetch) for a total of ten cropping systems. The authors also evaluated two additional systems that they referred to as ‘‘standard practice controls’’ (a winter fallow treatment with 140 kg ha^{-1} of N applied under disk tillage and a no-tillage treatment with a rye cover crop and 140 ha^{-1} of N applied). Direct and indirect energy requirements were calculated for all inputs (seed, fertilizer, machinery, labor, fuel, and herbicides). The authors found that corn production systems with legume cover crops supplying N had significantly lower energy expenditures than systems relying on manufactured N fertilizer. They also found that using either hairy vetch or a mixture of hairy vetch and bigflower vetch as winter-annual cover crops in no-tillage and reduced tillage systems provided enough N for economically competitive corn silage production. The profitability of these practices was equal to that of the ‘‘standard’’ corn production systems that required large amounts of manufactured N fertilizer.

Optimal N Application

Lichtenberg et al. (46) estimated N response functions for no-tillage corn following hairy vetch, crimson clover, Austrian winter pea, winter wheat, and fallow and used the response functions to estimate profit-maximizing N application rates and maxi-

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mum profits for each treatment. They used data from a three-year field study conducted in the Maryland Coastal Plain. The authors found that corn following hairy vetch produced the largest profits under a wide range of N fertilizer prices, vetch seed prices, and herbicide costs. The hairy vetch/corn rotation exhibited smaller N fertilizer savings relative to the wheat/corn or fallow/corn rotations at profit maximizing application rates. They concluded that hairy vetch increases the effectiveness of N fertilizer and thus produces greater corn yields at higher N application rates than crimson clover, winter wheat, fallow, or Austrian peas. The hairy vetch/corn rotation was also more profitable than the crimson clover/corn rotation because of the lower seed price for vetch.

Roberts et al. (47) calculated the quadratic yield response functions of no-tillage corn planted after hairy vetch, crimson clover, winter wheat, and no cover using experimentation data from Milan, Tennessee. They calculated a quadratic yield response function for each alternative using ten years of experimental plot data. They then calculated the profit-maximizing levels of N fertilizer and estimated the yields and net returns for each alternative at each profit-maximizing N level and found that the vetch and clover cover crops required less applied N for profit maximization than the no cover and wheat cover alternatives. Hairy vetch provided the highest profit-maximizing yield, while wheat provided the lowest. The wheat cover required the most applied N for profit maximization because the wheat crop consumed N that could be utilized by the following corn crop. They concluded that west Tennessee corn farmers may be able to reduce applied N fertilizer levels by switching from wheat cover and no cover systems to the hairy vetch cover system.

Economic Risk

Ott and Hargrove (48) used a safety-first criterion to evaluate the tradeoffs between average profit and variability of returns for crimson clover and hairy vetch cover crops in Georgia no-tillage corn production. The authors found that hairy vetch generated the largest average returns but also had the largest variance of returns relative to crimson clover. The safety-first analysis revealed that hairy vetch with 56 kg ha^{-1} of N was the preferred system for risk-neutral farmers, while hairy vetch with no N applied was the preferred system for risk-averse farmers in Georgia.

Hanson et al. (49) used a safety-first criterion to evaluate the profitability and economic risk of no-tillage corn following hairy vetch at two different locations in Maryland: Poplar Hill, MD (Coastal Plain location), and Ellicott City, MD (Piedmont location), for the years 1986 through 1988. At the Coastal Plain location, the yield advantage of corn following hairy vetch more than compensated for the expense of establishing hairy vetch. In all instances, corn following hairy vetch was the most profitable system evaluated. At the Piedmont location, the most profitable system was corn following winter fallow at 45 kg ha^{-1} of N fertilizer with corn following hairy vetch at 46 kg ha^{-1} of N fertilizer being the second most profitable system.

Although corn following hairy vetch had the highest yields at the Piedmont location, the higher yields were not always sufficient to cover the increased expense of seeding hairy vetch. In the Coastal Plain location, the best system for risk averse farmers was corn following hairy vetch with 134 kg ha^{-1} of N fertilizer. In the Piedmont location, the best system for risk averse farmers was corn following hairy vetch with 46 kg ha^{-1} of N fertilizer. The authors concluded that a hairy vetch cover crop system would be the most desirable system for risk averse farmers in both areas.

Larson et al. (50) used stochastic dominance to evaluate the profitability and net return variability of using winter cover crops for no-tillage corn production in west Tennessee. The authors evaluated no-tillage corn planted after hairy vetch, crimson clover, winter wheat, and no cover. Net return distributions were generated for each system using five different N rates (0, 56, 112, 168, and 224 kg ha^{-1} of N fertilizer). First-degree stochastic dominance (FSD) and second-degree stochastic dominance (SSD) were used to identify risk-efficient no-tillage corn cover crop rates. A hairy vetch system with 168 kg ha^{-1} of N fertilizer produced the largest expected net revenue of all the systems evaluated. This system was also included in the SSD efficient set. Thus, they concluded that risk averse farmers may choose this hairy vetch system to improve net revenue and soil quality. However, such a system would not reduce N fertilizer use when compared to the no cover N rate with the second largest expected return (no cover, 168 kg ha^{-1} of N fertilizer applied). These results indicated that hairy vetch cover crop systems may be used to maintain expected net revenues, but variability of net revenues with these systems may be increased with lower N application rates.

Giesler et al. (51) used generalized stochastic dominance to evaluate the relative economic feasibility of cover crop systems in Louisiana cotton production. Three cover crop systems (Austrian winter peas, hairy vetch, and common vetch) and two conventional systems (using 45 kg ha^{-1} of N fertilizer and 67 kg ha^{-1} of N fertilizer) were evaluated. Lower and upper risk aversion coefficients were calculated for sixteen risk aversion intervals, and risk premiums were calculated between the highest ranked cover crop system and the highest ranked conventional system. Two cover crop systems (hairy vetch and common vetch with 45 kg ha^{-1} of N fertilizer applied) were significantly dominant when compared to the conventional systems over the entire risk attitude spectrum. Thus, the authors concluded that cover crop systems may be feasible alternatives to conventional systems. The hairy vetch system was the dominant system over the range from mildly risk-preferring to extremely risk-averse, but its degree of dominance over the conventional systems decreased considerably as the level of risk aversion increased. The risk premiums between the hairy vetch system and the conventional 67 kg ha^{-1} of N fertilizer rate decreased as risk aversion increased, providing evidence as to why conventional practices have been so pervasive in cotton production.

Yiridoe et al. (52) used generalized stochastic dominance to identify risk-efficient cropping systems to replace the traditional cash crop of tobacco that is typically grown on light textured soils in Ontario. The authors wanted to determine if the productivity and profitability of bean/wheat systems could be increased through use of cover crops and conservation tillage. They evaluated 15 cropping systems that include various bean crops, tillage treatments, and cover crops. Kidney bean/wheat systems ranked first among the three bean/wheat rotations, followed by white bean/wheat rotations. Risk averse producers least preferred Soybean/wheat rotation systems. Within each bean/wheat rotation, no-tillage treatments tended to dominate conventional tillage treatments. The no-tillage corn cover crop kidney bean/wheat treatment was the most risk efficient choice for risk averse farmers.

Conclusions from Review of Grain Crop Studies

Several general conclusions can be drawn from the cover crop studies reviewed above. One is that legume cover crops such as hairy vetch and crimson clover are generally reported to be more profitable than grass cover crops such as rye or wheat due to the ability of legumes to contribute N to the following crop (41,46,47). Grass cover crops may in fact consume N that could be utilized by the following crop (47). Another conclusion is that incorporating legume cover crops into cropping systems may reduce the energy required for crop production (44,45) and reduce the level of N applied (43,47). Although these are important benefits for using cover crops, they may not always lead to increased profits to the farmer. The most important factors affecting the profitability of cover crops are their ability to enhance crop yields and to reduce their establishment cost. Several studies indicated hairy vetch systems are the most profitable cover crop systems, not because of reduced N application and energy savings (reductions in input costs), but because hairy vetch mulch improves soil structure and water-holding capacity and thus increases the effectiveness of applied N (46,49). In many studies, hairy vetch systems are reported to be more profitable at higher N application rates than at lower N rates (39,46,49,50). Some studies indicated returns in hairy vetch systems are less variable at higher N application rates (39,50). In studies where cover crop systems are reported to be less profitable than conventional systems, the lower profitability is attributed to the establishment cost of the cover crop (42,44,49). In these studies, the benefits of using the cover crop system (increased yields, reduced N applied) do not outweigh the establishment cost of the cover crop.

SUSTAINABLE VEGETABLE PRODUCTION

Fresh-Market Tomato Production: A Model System

Fresh-market tomatoes are conventionally grown on raised beds either uncovered (bare soil system) or covered with polyethylene mulch. The bare soil system involves a lower input than the polyethylene system. The former is more subject to weed

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pressure than the latter and depends on chemical (herbicides) or mechanical (cultivation and hand weeding) control of weeds. Commercial production of tomatoes uses polyethylene mulches. Water and nutrients are delivered through drip irrigation and pests are controlled through carefully planned schedules using integrated pest management systems.

Although polyethylene mulches add about \$1400 ha^{-1} to the production cost, yield increases and early maturity generate substantial additional profits to justify the additional production cost (38). However, there are major problems associated with these two conventional production systems. Both systems depend on commercial fertilizers for nutrition and on extensive tillage which induces soil erosion and compaction. In addition, polyethylene has been a source of environmental pollution due to its nondegradability. As a result of these deficiencies, environmentally healthy alternatives have been sought. One such alternative is to incorporate cover crops into vegetable production rotations in a no-tillage system to reduce dependence on commercial fertilizers, improve soil tilth, and reduce soil erosion and compaction.

Research has been conducted for over a decade at the Beltsville Agricultural Research Center with the objective of developing alternative vegetable production systems that utilize cover crops and reduce tillage. Hairy vetch alone or combined with other cover crops, such as crimson clover and rye, were used. Fresh-market tomatoes were used as a model vegetable (11). Comparisons were made among the bare soil, polyethylene and the alternative cover crop systems to include production cost and profitability (38), yield, earliness, fertilizer requirements, nutrient recycling, and organic matter production by the cover crop.

Growth analysis of tomatoes in response to black polyethylene or hairy vetch mulches revealed better growth early in the season but worse later in the season for plants grown in black polyethylene than in hairy vetch mulch (53). Unit leaf rate (rate of growth per unit leaf area) of fruit was higher with black polyethylene than with hairy vetch, whereas, the reverse was true of vegetation. This relationship led to a higher leaf area ratio and leaf area duration of plants grown with hairy vetch than with black polyethylene. Consequently, tomatoes grown with black polyethylene produced greater early yield, whereas those grown with hairy vetch eventually out-grew and out-yielded those grown with black polyethylene (29). Yields over a 5-year period were (in t ha^{-1}) 79 and 96 for black polyethylene and hairy vetch, respectively.

Hairy vetch alone produces an average of 5 t ha^{-1} of biomass and contains about 150–200 kg of N. When mixed with crimson clover and rye, biomass yields reach 9 to 10^{-1} with no reduction in N content (54). When the cover crop is killed chemically by herbicides or mechanically by mowing, the residues provide a plant mulch that suppresses weeds during the early period following transplanting the tomatoes. One application of herbicides often is needed 3–4 weeks following transplanting to kill any regrowth especially if the cover crop was terminated early (before flowering) and if the weather was cool.

Nitrogen requirements by fresh-market tomatoes grown on hairy vetch were evaluated over a 3-year period (11). In these experiments, ''Sunbeam'' tomatoes were grown on polyethylene and hairy vetch mulches. N was applied in the form of ammonium nitrate commercial fertilizer at weekly intervals through the drip system at the rates of 0, 56, 112, 168, 224, 280, 336, and 392 kg ha^{-1} per season. The hairy vetch treatment yielded 3.3 to 4.5 t ha^{-1} of biomass resulting in N content of 126 to 169 kg ha^{-1}. Tomato yields increased in response to applied N in both mulches in all three years. Optimum N rates were 89 and 190 kg ha^{-1} for tomatoes on hairy vetch and black polyethylene mulches, respectively. Hence, a saving of 100 kg ha^{-1} of N was realized on hairy vetch mulch compared to polyethylene mulch.

The hairy vetch cover cropping system that was developed for fresh-market tomatoes was applied to processing tomatoes (55). Yields of ten processing tomato cultivars in hairy vetch average 32% higher than those in bare soil or polyethylene mulch. The fruits were also larger and plant necrosis was lower in hairy vetch than in the other two systems. Similar results were exhibited in snap beans where the plants were larger and yields were 50 to 100% higher in hairy vetch than in bare soil (56). In all these comparisons, plants in the hairy vetch system received half the amount of commercial fertilizer N applied to the bare soil or the black polyethylene mulch treatments. The cover crop residues provided the rest of the N. Research is in progress to apply the cover crop production system to peppers, sweet corn, and cucurbits. A Farmers' Bulletin which describes the hairy vetch system for growing tomatoes and other summer vegetables has been published (11).

Economic Analysis of Fresh-Market Tomato Production

This section compares the profitability and economic risk of the hairy vetch mulch (sustainable) system described above with the bare soil and black polyethylene mulch (conventional) systems for fresh-market tomato production under conditions commonly faced by tomato growers in the mid-Atlantic states. The study is described in detail in Kelly et al. (38). The experiments were conducted over three years, 1991–1993, at the Beltsville Agricultural Research Center in Maryland on Keyport fine sandy loam soil with 2 percent slope. Detailed procedures about these experiments are described in Abdul-Baki et al. (29).

Production costs were derived from vegetable crop budgets for Maryland, Delaware, and Virginia (57–59). Field operations and amounts of chemical inputs used reflect actual operations at the experimental site. Fertilizer costs represent the amounts typically used in the mid-Atlantic region, with the vetch system receiving only half the typical rate of N. Machinery, labor, and fixed costs were calculated from state crop budgets and reflect those realistically faced by farmers. Prices for chemicals were the March 1994 prices from Southern States Cooperative in Baltimore, MD and were deflated for earlier years to reflect rising input prices over time.

Labor charges were $6.00 per hour in 1993 and were similarly deflated for earlier years. Input costs were based on indices of production costs taken from *Agricultural Statistics 1993* (60). Interest on operating expenses was for six months at 12 percent per annum. Harvest and marketing costs changed with varying yield levels. Land rent and depreciation on buildings were not included since they were the same for all systems.

Gross returns were calculated by matching the actual weekly harvested tomatoes with the appropriate weekly price summed over the total number of harvests for each of the three years. Weekly prices for the three years were obtained from two markets: the Southern Maryland Regional Farmers' Market in Cheltenham, MD, and the Baltimore Fresh Fruit and Vegetable Wholesale Market in Jessup, MD. Tomato prices varied considerably from week to week and between the two markets. On average, the Jessup price was higher than the Cheltenham price, although the Cheltenham price increased toward the end of the season relative to the Jessup price. The three-year average median price for Maryland large tomatoes during this 11-week period was $7.06 per box at Jessup, while the average weighted mean tomato price at Cheltenham was $6.25 per box.

Weather was the major cause of yield variability. The weather conditions varied considerably during the three years of the experiments. The first year was the best with high temperatures, good radiation, and a favorable distribution of rainfall. The second year was characterized by cool temperatures, low radiation, and higher rainfall, especially during the establishment period. This condition resulted in higher disease pressure which tended to have a greater effect on the bare soil and polyethylene systems. High temperatures, high radiation, and lack of rainfall, particularly during the growth period, characterized the third year. These conditions tended to favor the black polyethylene system.

Total tomato yields for the three systems are presented in Table 3. It is apparent from the data that tomatoes grown with hairy vetch mulch out-yielded those grown with black polyethylene and no mulch in all three years. The hairy vetch system was also the most profitable system among the three systems in all years, in both markets, and under all weather conditions as shown Table 4.

Table 3. Marketable Tomato Yields for the Three Production Systems

	Yield (t ha^{-1})		
Production system	1991	1992	1993
Bare soil	53.4	35.5	77.3
Black polyethylene	107.3	45.3	88.0
Hairy vetch	129.2	85.8	95.8

Table 4. 1991 Returns to Management, Land, and Buildings ($ ha^{-1})

	Jessup market			Cheltenham market		
Year	Bare soil	Black polyethylene	Hairy vetch	Bare soil	Black polyethylene	Hairy vetch
1991	7,308	20,210	25,060	5,047	13,909	26,880
1992	3,240	5,781	14,488	773	789	14,784
1993	27,094	27,639	39,992	18,569	20,000	25,071
Average	12,547	17,877	26,513	8,130	11,566	22,245

The higher relative profitability of the vetch system was due in part to higher yields with a lower cost structure, and also due to higher late season prices. Although tomatoes grown with black polyethylene mature more quickly and provide earlier yields when prices are usually higher, the later-yielding hairy vetch system took advantage of the higher prices later in the season. This situation is typical of Maryland where tomato harvest in neighboring southern states (such as the Carolinas) are several weeks earlier and the market gets saturated, reducing the premium prices of early production in Maryland.

Farming, particularly vegetable production, is a high-risk business because of yield and price variability. In this study, a ‘‘safety-first’’ criterion is used to evaluate economic risk. This method is consistent with maximizing expected profits, where profits are used as a proxy for utility (61). The coefficient of variation measures the extent that profits deviate from the mean, both upward and downward. However, farmers are concerned about the downward deviations and not the upward deviations. The safety-first criterion assumes that the decision maker wants to maximize profits subject to the probability that profits will be greater than a specified disaster level. For empirical applications, the lower confidence limit of profits has been used to specify the disaster level. The lower confidence limit of profits for a particular activity, the ith system in this case, can be calculated as

$$L_i = E_i - K\sigma_i$$

where

E_i = expected profits
K = the number of standard deviations required to impose the desired probability that E_i is greater than L_i
σ_i = the standard deviation of profits for activity i.

The sample size for each treatment is the total number of replications in all three years, and is 28 for the bare soil and hairy vetch systems and 24 for the black polyethylene system. We assume that returns are normally distributed. At the 75 percent confidence level, K is 0.683 for bare soil and hairy vetch systems and 0.684 for black

Table 5. 75 Percent Lower Limit of Returns ($\$ \cdot ha^{-1}$)

Production system	Returns per hector
Bare soil	3,269
Black polyethylene	8,962
Hairy vetch	18,021

polyethylene. In the risk analysis of the market choice, the expected (mean) returns and the standard deviation of returns are calculated separately for each system, then averaged across systems in order to isolate market variability from variability across systems.

The lower limits of returns for the three systems at the 75 percent confidence level are presented in Table 5. The results indicated that the hairy vetch system was most profitable and also the least risky of the three systems. The return per hectare for this system is expected to exceed $18,021 in three out of four years. The actual experimental yields were used in this analysis. These results indicated that a risk-averse farmer would prefer the hairy vetch mulch system for growing fresh-market tomatoes.

The results of economic analysis indicated that returns to land, buildings, and management from the hairy vetch system were consistently higher and less risky than those from the black polyethylene system, which is considered the industry standard. The profitability advantage of the hairy vetch system is due to greater yields, later production which coincided with higher late season prices, and lower inputs as a result of eliminating black polyethylene and reducing N applications.

SUSTAINABLE GRAIN PRODUCTION

Grain Production Systems Using Cover Crops

Cover crops often are more difficult to fit into grain than into vegetable crop rotations because there is less time available for establishing cover crops after harvesting grain crops in fall and profit margins are narrower in grain than in vegetable crops. Nonetheless, cover crops can offer many of the advantages described earlier and, consequently, have been studied extensively for agronomic and economic benefits to grain cropping systems. The management of cover crops is an important factor in determining the realization of these benefits.

Research has been conducted in the mid-Atlantic states to determine optimum management programs for growing corn in a hairy vetch cover crop. Hairy vetch has been shown to reduce N requirements of corn and enhance corn yields at optimum N rates (10). Yield enhancement at optimum N rate may be explained by improved soil physical properties (14) and soil moisture retention (62) by the hairy vetch mulch. Improved corn yield has been shown when hairy vetch was killed 1–3 weeks before planting (preplant) rather than immediately after planting (preemergence) or after corn emergence (postemergence) (31) (see Table 6). Although it may seem that delaying vetch kill would be advantageous because of increased vetch biomass and N content, these advantages were offset by a number of factors. Thicker vetch biomass can interfere with no-tillage planting operations or can encourage destructive insect populations leading to reduced corn stands (Table 6). Also, delayed vetch kill can result in greater soil moisture removal which can reduce yields if followed by a summer drought. Therefore, many factors need to be balanced to achieve optimum management of cover crops for grain production.

A long-term Sustainable Agricultural Demonstration site was established at the Beltsville Agricultural Research Center to compare four grain cropping systems that varied in cover crop use and management. Analysis of these systems illustrates several tradeoffs that can be encountered by introducing cover crops into grain crop rotations. Table 7 summarizes these cropping systems. The no-tillage system (NT) represents a common rotation in the mid-Atlantic states using recommended fertilizer and herbicide inputs but no cover crop. The crown vetch system (CV) is similar to the no-tillage system except that crops are grown in a perennial crown vetch living mulch. The cover crop system (CC) adds the winter annual cover crops hairy vetch before corn and wheat before soybean. The manure-based system (MN) substitutes cow and green manures for fertilizers and mechanical weed control for herbicides.

The absence of tillage and presence of crop residue on the soil surface can lead to improved soil tilth and reduced soil erosion in no-tillage versus plow-tillage systems (63,64). The crown vetch living mulch system has the potential to improve soil tilth, reduce erosion, and reduce herbicide runoff more than desiccated residue in a no-

Table 6. Influence of Time of Killing a Hairy Vetch Cover Crop Relative to Time of Planting Corn on Hairy Vetch Biomass and N Content and Corn Yield and Population Averaged Over Four Experiments

	Hairy vetch		Corn	
Timing	Biomass	N Content	Yield	Population
	kg ha^{-1}			1000 ha^{-1}
Preplant	2840	107	10,550	57.0
Preemergence	4640	157	9,930	52.3
Postemergence	4820	157	9,350	52.1

Vetch was killed either 1–3 weeks before planting corn (preplant), immediately after planting corn (preemergence), or after corn emergence (postemergence).

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Table 7. Essential Features of Cropping Systems at the Sustainable Agricultural Demonstration Site, Beltsville, Maryland, 1994–1997

Operation	No-tillage system	Crown vetch system	Cover crop system	Manure-based system
Crop year 1	Corn	Corn	Corn	Corn
Crop year 2	Wheat/Soybean	Wheat/Soybean	Soybean	Wheat/Soybean
Tillage	None	None	None	Chisel plow/disk
Cover crops	None	Crown vetch living mulch	Hairy vetch before corn, wheat before soybeans	Crimson clover before corn
Nutrient source	Fertilizer	Fertilizer + crown vetch residue	Fertilizer + hairy vetch residue	Cow manure + crimson clover residue
Week control	Preemergence + postemergence herbicides	Preemergence + postemergence herbicides	Cover crop residue + post-emergence herbicides	Preplant tillage + postplant rotary hoe and cultivation

tillage field (65). However, competition between the living crown vetch and corn led to a corn yield reduction in CV relative to NT when averaged over the first four years of study (Table 8). The high cost of establishing this living mulch species coupled with potential corn yield reductions make this system too unpredictable for use by growers at present.

The addition of winter annual cover crops into the rotation requires the elimination of winter wheat as a rotational crop. However, a hairy vetch cover crop before corn permits the reduction of fertilizer and herbicide inputs while maintaining four-year average corn yields in CC at similar levels to NT (Table 8). Also, soybean yields were almost doubled with lower herbicide inputs in CC compared to NT because a full-season crop could be grown in CC compared to a double crop in NT. As a result, the cover crops permitted similar or improved production of corn and soybeans with lower inputs than the traditional no-tillage system.

Table 8. Four-Year Average Grain Yields (t ha^{-1}) of Four Alternative Cropping Systems

System	Corn	Wheat	Soybean
No-tillage (NT)	7.82	3.15	1.52
Crown vetch (CV)	6.44	4.07	1.58
Cover crop (CC)	7.86	—	2.70
Manure (MN)	5.66	3.11	1.44

Complete elimination of fertilizer and herbicide inputs in the MN system required tillage with a chisel plow to permit incorporation of cow manure and mechanical cultivation for weed control. Cow manure supplemented an overseeded crimson clover green manure crop to provide nutrient requirements for corn and provided all nutrient requirements for wheat. This system reduced four-year average corn yield compared to all other treatments primarily because of inadequate weed control but provided similar wheat and soybean yield to the NT system (Table 8). Although this system has the benefit of eliminating all synthetic inputs, the required tillage increases the potential for erosion and poor weed control increases the potential for yield reductions. More research is needed to develop cover crop management systems that will allow elimination of synthetic inputs in no-tillage rotations.

Economic Analysis of Grain Production

This section compares the profitability and economic risk of the CC system with three other systems at the Beltsville Sustainable Agricultural Demonstration site described in the above section. Crop prices used were annual prices for the period 1994 through 1997 (Maryland Agri-Facts, various years). Since wheat grain was contaminated by wild garlic and could not be sold as milling quality, the annual price for wheat was adjusted to a feed grain price by taking the lesser of either the annual corn price plus \$19.68 t^{-1} (\$0.50 bu^{-1}) or the annual wheat price. Nominal prices were adjusted to 1993 constant dollars using the Consumer Price Index. The price for wheat straw was held constant at \$105.84 t^{-1} (\$1.20/25 pound bale) during all years.

The quantities of seeds, fertilizers, and chemicals used were actual values for the demonstration farm, with their respective prices. The typical custom hire charges represent 1993 prices for the state of Maryland (66) and are used for all years. These charges were assumed to cover labor, machinery operating and depreciation costs, and associated insurance and taxes. Custom hire charges were used instead of breaking down individual operations and costing the components.

Seed, fertilizer, and chemical costs were provided by Johnson (66) and are indicative of costs faced by farmers in 1994. Operating interest is for 6 months at an annual rate of 12%. Total variable production costs for each rotation are calculated as the simple average of the two rotation components (corn and wheat/soybean/straw), assuming that half the area is planted to each component. It is assumed that the farmer has both crop and livestock production and thus there is no cost for manure except for the application cost.

Gross margins for the four cropping systems from 1994 to 1997 are summarized in Table 9. Gross margin is the total returns less total variable costs. We assume that both years of the rotation are represented in a hectare and thus the returns by crop shown in the table are for a half hectare. Total returns are simply the sum of

Table 9. Gross Margins and 75 Percent Safety-First Lower Limits

Year	NT	CV	CC	MN
	$ ha^{-1}			
1994	428	18	492	510
1995	294	−80	169	433
1996	362	466	415	169
1997	−15	−19	−124	−243
Average	233	53	238	217
Lower limit	53	−143	39	−14

returns of the individual crops. For the average of four years, the CC system provided the greatest gross margins ($238.28 ha^{-1}), partly because of the highest average corn yields, followed by the no-till system ($233.27 ha^{-1}) and the MN system ($217.35 ha^{-1}). The average gross margin for the CV system was the lowest ($53.34 ha^{-1}).

The MN system returned more gross margins than all other systems during 1994 and 1995 but had the smallest gross margins during 1996 and 1997. Poor crop yields in the last two years due to increased weed competition contributed to smaller gross margins. The MN system could become more profitable relative to the other three systems if weeds could be controlled. Also, the MN system has the potential to become the most profitable of the four systems, since its crops can be certified as organic and sold at premium prices.

Risk Analysis

Farming is a risky business, and farmers are constantly facing uncertainty due to unpredictable factors such as price variability, weather, diseases, pests, etc. Generally, farmers want to select a cropping system that generates the largest profits, but the variability of profits, or economic risks, can also affect the desirability of the cropping system. Farmers respond to risks in different ways. A risk neutral farmer will select the cropping system that generates the largest expected (or average) profit without regard to variability of profits. In this study, a risk neutral farmer would prefer the CC system, since it generates the largest average gross margin of the four systems evaluated. Alternatively, a risk averse farmer is more concerned with the variability of profits and would be willing to sacrifice higher profits to achieve more stable profits.

The safety-first criterion indicated earlier (67,68) is also used to evaluate economic risk of the four systems. Assume that profits are normally distributed. For $K = 0.675$ in a normal distribution, the probability that gross margins will be greater than or less than $K\sigma_i$ from the mean is 50 percent. That is, the probability that the gross margin will be below $L_i = E_i - K\sigma_i$ is 25 percent and the probability that the gross

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margin will be above $U_i = E_i + K\sigma_i$ is 25 percent (where U_i is the upper confidence limit). Farmers are only concerned with the lower limit. Thus, the farmer can expect to have profits at least $\$L_i$ in three out of four years. For example, the mean and standard deviation of gross margins for the NT system are \$233.67 ha^{-1} and \$267.00 ha^{-1}, respectively. At the 75 percent confidence interval, the lower confidence limit for the NT system is \$53.31 ha^{-1}. That means the farmers can expect to receive a gross margin of at least \$53.31 ha^{-1} in three out of four years using the NT system.

Table 9 shows the lower limits of gross margins at the 75% risk confidence level for the four cropping systems. These results indicated that the NT system has the smallest risks. Three out of four years, the average gross margins for the NT system are expected to exceed \$53.31 ha^{-1} as indicated above. The CC system has the second smallest risks with the lower confidence limit of \$39.21 ha^{-1}, followed by the MN system with a −\$14.38 ha^{-1} lower confidence limit. The CV system has the largest risks with the confidence limit of −\$142.54 ha^{-1}.

The risks measured for the 1994–1997 period probably overestimated the variability of crop yields in the mid-Atlantic states. Weather conditions during this period were extremely variable, ranging from unusually good years in 1994 and 1996 to an extremely dry year in 1997. Therefore, results of economic and risk analyses based on the four years of yield data can not be considered ‘‘typical’’ or ‘‘representative.’’ Different ranking of profits and risks could emerge for a typical or representative year. More data are needed to assess long-term profitability and risks.

Sensitivity Analysis

The relative profitability of the four cropping systems depends on relative prices, especially the input prices. The four systems use different sources of N. The NT and crown vetch systems use chemical fertilizers, the CC system uses hairy vetch, and the MN system uses animal and green manures. We evaluated the impacts of changes in relative prices on the relative profitability of these three systems. The CV system was not included in the comparison because it is the least attractive in terms of profitability and risks, and changes in relative prices would not make it more attractive than the other cropping systems.

The CC system, the most profitable of the four systems, uses hairy vetch as a major source of N. Recently, the prices of hairy vetch seed has been quite variable, and farmers are concerned about the cost. Since the cost of hairy vetch seed constitutes only a small part of the total costs (2.7 percent in 1996), changes in their prices are not likely to affect the ranking of profitability.

The NT system, the second most profitable system, uses chemical fertilizers. The average price for N fertilizer in 1993 dollars from 1989 through 1996 was 54 cents kg^{-1} with a standard deviation of 6 cents kg^{-1}. N fertilizer prices have been trending upward in recent years. Assume the trend will continue. If the N fertilizer price increases one standard deviation (6 cents kg^{-1}) and prices of phosphorus (P) and potash (K) also increase proportionally, that is, the prices of N, P, and K increase from 55, 55, and 35 cents kg^{-1}, respectively, to 60, 60, and 38.85 cents kg^{-1}, the NT system would still be more profitable than the MN system, which ranks third in profitability. Prices for N, P, and *K* would have to increase by 12 percent to 61.6, 61.6, and 38.8 cents kg^{-1}, respectively, to make the MN system more profitable than the NT system. Since the NT system also uses herbicides to control weeds, increases in both fertilizer and herbicide prices of less than 12 percent will make the MN system more profitable.

The MN system derives plant nutrients from animal and green manures and does not use commercial fertilizers and chemicals. It is an organic farming system. The costs for using animal manures include processing, storage, transportation, field applications, and purchasing of manures. The cost for purchasing animal manures can be negative if livestock producers have excess manures to dispose of and pay crop growers to haul away the manures. The cost of transportation is a dominant factor. It depends on the water content of the animal manures, the hauling distance from a storage site to the application field, and the number of trips required to supply the amount of manures needed to provide enough nutrients for crop growth. Thus, the costs of animal manure application can vary considerably from farm to farm. If livestock farmers subsidize crop growers for using manures, and the costs of animal manure application drop from \$2.21 t^{-1} to less than \$1.10 t^{-1}, the MN system will become most profitable.

Since the MN system is an organic system, its crops can be certified as organic and sold at premium prices. Premium prices would only need to be 3.5 percent higher than prices for conventional crops for the MN system to be the most profitable of the four systems evaluated.

Note the weather conditions during the 1994–1997 period were extremely unusual and thus the results of the economic and risk analyses based on the four years of yield data can not be considered ‘‘typical’’ or ‘‘representative.’’ In the next section, we will evaluate long-term profitability and risks along with environmental impacts of these alternative-cropping systems.

LONG-TERM IMPACTS OF COVER CROP SYSTEMS

A shortcoming of many of the economic cover crop studies is that they are short-term studies. In much of the previous work, the profitability of cover crops is based on one to four years of experimental data. Another shortcoming is the lack of knowledge about the long-term impacts of cover crop systems on the environment. Cover crops such as hairy vetch and crimson clover add N to following crops, aid in the reduction of soil erosion, improve water filtration, and enhance the effectiveness of applied N fertilizer. However, improved water filtration may lead to increased leaching of agricultural chemicals into groundwater supplies. What impact will the adoption of cover crop systems have on groundwater and surface water quality in the long run? Will these systems improve economic returns relative to conventional strategies in the long run? Will use of these systems increase economic risk over time? These are questions currently in need of answers.

Biological Simulation

Biological simulation models can be used to evaluate the long-term economic and environmental sustainability of cover crop systems. We have applied simulation analysis to evaluate long-term effects of cropping systems at the Sustainable Agriculture Demonstration Site at Beltsville, Maryland, discussed in the previous section. Preliminary economic findings from the first four harvest years indicated that the CV system is unprofitable compared to the three other systems. Therefore, we excluded CV from the simulation analysis. The EPIC (Environmental Policy Integrated Climate) biological process simulation model was calibrated to simulate the remaining three cropping systems using production, input, tillage, soil, and daily weather data from the Sustainable Agricultural Demonstration site for the period 1994 through 1997. EPIC is a simulation model designed to help decision makers determine the impacts of alternative cropping systems and climate conditions on crop productivity, soil degradation, and water quality (69). Its components include weather, hydrology, erosion, nutrient cycling, pesticide fate, soil temperature, tillage, crop growth, crop and soil management, and economics (69,70).

After calibration, the EPIC model was used to simulate crop yields, pesticide losses, N and P losses, and soil erosion for the NT, CC, and MN cropping systems over a sixty-year period. In addition, two alternative systems were added to the simulation analysis:

- Cover Crop, Zero (CCZ). Same as CC except no fertilizer is applied.
- Corn/Soybean Rotation (CS). A no-tillage two-year rotation of corn followed by full season soybeans with recommended fertilizer and herbicide inputs.

The CCZ system was added to determine if the hairy vetch cover crop provides sufficient N fertilizer for corn. CS was included to determine if removing winter wheat from the cropping system increases profits, since winter wheat experiences weed problems in the study region. The CS system is essentially the same as the NT system with the exception that winter wheat is not grown in the second year of the rotation.

Output from EPIC was used to construct two economic and three environmental evaluation variables for each cropping system. The economic variables were the average gross margin and the 75 percent safety-first lower limit of returns for each cropping system. As indicated earlier, we define gross margin as gross returns less seed costs, fertilizer costs, pesticide costs, custom hire charges, and operating interest. The custom hire charges were assumed to cover labor, machinery operating and depreciation costs, and associated insurance and taxes. Gross margins were calculated in 1994 dollars. The 75 percent safety-first lower limit was used to evaluate the economic risk of each cropping system.

The three environmental variables were average soil erosion, the average pesticide hazard index, and the average nutrient hazard index for each cropping system. Most crop production in the mid-Atlantic occurs on small farm fields with steep slopes. Therefore, soil loss from erosion is a major consideration for most farmers in the area. We used simulated annual soil erosion to evaluate the relative effectiveness of erosion control for each cropping system.

Pesticide and Nutrient Hazard Indices

Each cropping system has different herbicide programs (Table 10). The NT and CS systems apply preplant/preemergence herbicides and postemergence herbicides, the two cover crop strategies (CC and CCZ) apply only postemergence herbicides, and the MN strategy applies no herbicides. Pesticide hazard indices were calculated to evaluate the environmental hazards of herbicide application for each cropping system to both surface water and groundwater supplies. The pesticide hazard indices were calculated using a method similar to that proposed by Teague et al. (71). The method weighs the movements of each pesticide (runoff, sediment, and percolation in g ha^{-1}) by their associated level of toxicity. Different toxicity weights were calculated for both groundwater movements (pesticide leachate) and surface water movements (herbicide runoff plus sediment). Surface water and groundwater hazards were weighted equally. They were then summed to represent the pesticide hazard index for each herbicide. The pesticide hazard index for each cropping system was calculated as the sum of the pesticide hazard indices for all herbicides used in the cropping system.

Each cropping system also has different nutrient programs (Table 11). Nutrient hazard indices were also calculated for each cropping system based on simulated N movement in runoff, sediment, and leachate (kg ha^{-1}) and P movement in both runoff and sediment (kg ha^{-1}). Nitrate N movement in runoff plus organic N movement in sediment was defined as the surface water hazard, while nitrate N leachate was defined as the groundwater hazard for N. Nitrogen groundwater and surface water hazards were weighted equally by multiplying each hazard by 0.5. They were then summed to represent the N hazard index for each cropping system. The P hazard index considered only surface water hazard (soluble P loss in runoff plus P sediment), since P does not percolate as readily as N and also does not have any notable adverse health effects to humans. The nutrient hazard index for each cropping system was thus calculated as the N hazard index plus the P hazard index.

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Table 10. Herbicides and Annual Herbicide Rates Used in Long-Term Simulations of Cropping Systems at the Sustainable Agriculture Demonstration Site, Beltsville, Maryland

Herbicide	Type[a]	NT	CC	CCZ	CS	MN
		Rate (kg a.i. ha^{-1})				
Corn year:						
Metolachlor	Pre	2.24	—	—	2.24	—
Atrazine	Pre	1.79	—	—	1.79	—
Paraquat	Pre	0.53	—	—	0.53	—
Linuron	Pre	—	—	—	—	—
2, 4-D	Pre	1.12	—	—	1.12	—
Nicosulfuron	Post	0.05	0.05	0.05	0.05	—
Dicamba	Post	—	0.56	0.56	—	—
Thifensulfuron	Post	—	—	—	—	—
Glyphosate	Post	—	—	—	—	—
Wheat/Soybean year:						
Metolachlor	Pre	0.93	—	—	0.93	—
Atrazine	Pre	—	—	—	—	—
Paraquat	Pre	0.53	—	—	0.53	—
Linuron	Pre	2.24	—	—	2.24	—
2. 4-D	Pre	—	—	—	—	—
Nicosulfuron	Post	—	—	—	—	—
Dicamba	Post	—	—	—	—	—
Thifensulfuron	Post	0.04	—	—	—	—
Glyphosate	Post	—	1.68	1.68	—	—

[a] Pre = preplant or preemergence herbicide; Post = postemergence herbicide.

Table 11. Annual Nutrient Rates for Long-Term Simulations of Cropping Systems at the Sustainable Agriculture Demonstration Site, Beltsville, Maryland

	NT	CC	CCZ	CS	MN
Corn year:					
mineral N (kg ha^{-1})	194	106	—	194	—
mineral P (kg ha^{-1})	30	30	—	30	—
manure (t ha^{-1})[a]	—	—	—	—	24
Wheat/Soybean year:					
mineral N (kg ha^{-1})	93	—	—	—	—
mineral P (kg ha^{-1})	31	—	—	—	—
manure (t ha^{-1})	—	—	—	—	20

[a] Cow manure (0% mineral N, 0.7% organic N, 0.2% mineral P, and 0.1% organic P).

Results of the Simulation Analysis

The average gross margin for each of the five cropping systems is presented in Table 12. The CS system had the largest average gross margin (\$305 ha^{-1}). CS produced a larger average gross margin than NT because of larger yields and lower custom and input costs resulting from the exclusion of a wheat crop in the second year of the two-year rotation. CS was the most profitable of the five cropping systems because of larger average crop yields. The CC system was the second most profitable (average gross margin = \$270 ha^{-1}). CC had a cost advantage over NT because of the hairy vetch cover crop in the corn year of the rotation. Inclusion of the cover crop resulted in reduced herbicide and fertilizer application costs for the system. CCZ was the least profitable system over the sixty-year simulation (average gross margin = \$196 ha^{-1}). CCZ had smaller input costs than the other four systems because no fertilizer or preemergence herbicides was applied. However, crop yields for the CCZ system declined over time due to depletion of soil nitrogen. This result conforms with findings from other studies which indicated legume cover crops by themselves do not provide adequate N for profitable crop production (39,41,50).

The CS system had the largest safety-first lower limit (\$173 ha^{-1}) (Table 12). Thus, CS had the smallest economic risks of five systems evaluated. CC was the second least risky system (safety-first lower limit = \$130 ha^{-1}), followed by MN (safety-first lower limit = \$108 ha^{-1}). CCZ and NT were the most risky of the five systems evaluated. CCZ was the most risky system primarily because of deterioration of yields over time from depletion of soil N. NT was more risky than CS because of lower crop yields, and was more risky than CC and MN because of higher herbicide and fertilizer costs, which made profit margins smaller for NT than for either CC or MN during bad crop years.

Table 12. Variables Used to Evaluate Long-Term Impacts of Cropping Systems at the Sustainable Agriculture Demonstration Site in Beltsville, Maryland

Evaluation variable[a]	NT[b]	CC	CCZ	CS	MN
Economic:					
Average gross margin (\$ ha^{-1})	228	270	196	305	244
75 percent lower limit (\$ ha^{-1})	74	130	54	173	108
Environmental:					
Average soil erosion (t ha^{-})	10	12	12	13	112
Average pesticide hazard index	345	34	32	348	0
Average nutrient hazard index	22	28	20	31	29

[a] Each evaluation variable is calculated based on sixty simulation years for each cropping system. Each cropping system was simulated using EPIC.
[b] No-tillage, CC = cover crop, CCZ = cover crop-zero, CS = corn/soybean, and MN = manure.

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The average soil erosion for each of the five cropping systems is also presented in Table 12. There is very little difference in average soil erosion between the five cropping systems. Thus the relative effectiveness of soil erosion control is nearly the same for each system. CS produced a slightly larger amount of soil erosion than the other four systems because it excluded a winter wheat crop. The exclusion of winter wheat resulted in greater soil exposure to rainfall in the winter and early spring months of the cropping system. NT produced the least amount of soil erosion. This result may have occurred because winter wheat occupied more time than soybeans in the NT system when compared to the two cover crop strategies. NT had a slightly smaller level of average soil erosion than MN because of the difference in the mode of tillage used for each system: no-tillage for NT and reduced tillage for MN.

The average pesticide hazard indices are presented for each cropping system in Table 12. MN had a zero pesticide hazard index because no herbicides were applied with this system. CC and CCZ had significantly smaller pesticide hazard indices than either NT or CS because the two cover crop systems excluded preemergence herbicides. The preemergence herbicides in this study tended to have higher toxicity weights than the postemergence herbicides. The preemergence herbicides also tended to have larger runoff and leachate losses.

The average nutrient hazard indices for each cropping system are presented in Table 12. CCZ had the smallest nutrient hazard index. The nutrient hazard index for CCZ was smallest because no fertilizer was applied in this cropping system. CS had the largest nutrient hazard index due to a large amount of nitrate leachate resulting from exclusion of a winter wheat crop. The winter wheat crop would normally remove soil moisture and soil N during the winter and early spring months. Since winter wheat was absent in the CS system, soil N percolated more readily when compared to the other four systems.

It is evident based on the simulation results presented above that there were tradeoffs between economic and environmental objectives among the three most profitable cropping systems, CS, CC, and MN. CS was more profitable on average and less risky than either CC or MN.

However, CS had a larger nutrient hazard index, a larger pesticide hazard index, and a larger level of soil erosion than either CC or MN. Therefore, a tradeoff in objectives existed between the more profitable and less risky CS strategy and the more environmentally sound CC and MN strategies. There were also economic and environmental tradeoffs between CC and MN. In this instance, CC was more profitable and less risky when compared to MN, but MN had a smaller (zero) pesticide hazard index than CC.

The simulation results also demonstrated the environmental and economic importance of incorporating hairy vetch into the cropping system. The most significant environmental outcome resulting from the use of hairy vetch as a cover crop before corn was reduced herbicide application. Since hairy vetch suppressed weed emergence, preemergence herbicides were not necessary for either CC or CCZ. Thus, the pesticide hazard indices for these cropping systems were significantly smaller than those for NT or CS. The major economic benefit of using hairy vetch was reduced input costs resulting from fewer herbicide applications and less fertilizer application. This made the CC system more profitable and less risky over the long-term than the NT system. There appeared to be a tradeoff between high profitability and potentially higher nutrient loss in the CC system. When nitrogen was withheld from the CC system (as in the CCZ system), nutrient hazard was reduced but so was profitability.

SUMMARY AND CONCLUSIONS

This paper reviewed the literature on the benefits and limitations of using cover crops in sustainable food production, reported the experimental results using cover crops in sustainable horticultural crop production and sustainable grain production at Beltsville Agricultural Research Center, Maryland, and evaluated the long-term economic and environmental impacts of using cover crops in grain cropping systems. Cover crops have been shown to reduce soil erosion, provide nutrients for plant growth, improve soil organic content, increase soil water-holding capacity, control pests, reduce weed competition, and reduce need for herbicides.

Economic research investigating the profitability of cover crops in horticultural systems is still in the beginning stages. Nevertheless, we can speculate from the review of the work completed thus far that reducing input costs with cover crops may not be enough to increase profitability. Crop yields must also be enhanced. In our study at the Beltsville Agricultural Center on fresh-market tomatoes, the results indicated that tomatoes grown with hairy vetch mulch out-yielded those grown with black polyethylene and no mulch in all three years. The hairy vetch system was also the most profitable system among the three systems in all years, in both markets, and under all weather conditions. The relative profitability of the hairy vetch system is due both to higher yields and to later production which coincided with higher late season prices. Previous economic studies of the use of cover crops in grain production reported that legume cover crops such as hairy vetch and crimson clover are generally more profitable than grass cover crops such as rye or wheat due to the ability of legumes to contribute N to the following crop. The most important factors affecting the profitability of cover crops are their ability to enhance crop yields and to reduce their establishment cost. Several studies indicated that hairy vetch systems are the most profitable cover crop systems, because they reduced N application, saved energy, improved soil structure and water-holding capacity, and thus increased the effectiveness of applied N. In many studies, hairy vetch systems are reported to be more profitable at higher N application rates rather than at lower N rates.

The results of our comparative analysis at the Sustainable Agricultural Demonstration site at the Beltsville Agricultural Research Center of four reduced-tillage crop-

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ping systems indicated that the CC-based system produced the larger average gross margin than a recommended NT system or an organic MN system. The results of 60-year EPIC simulations demonstrated the environmental and economic importance of including hairy vetch in the cropping system. The CC system maintained a high gross margin while reducing pesticide hazards to approximately one-tenth of recommended no-tillage systems. Hairy vetch suppressed weed emergence and thus reduced or eliminated the application of preplant or preemergence herbicides in the cropping system. Inclusion of hairy vetch also resulted in lower herbicide and fertilizer costs for the CC system when compared to the conventional NT system.

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